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MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 88
Numbers 9-12

SEPTEMBER—DECEMBER 1960

Closed November 15, 1960
Issued December 15, 1960

SATELLITE PICTURES OF A CUT-OFF CYCLONE OVER THE EASTERN PACIFIC*

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[Manuscript received October 10, 1960; revised October 24, 1960]

ABSTRACT

TIROS I photographs taken near the most intense stage of a cut-off cyclone over the eastern Pacific are examined relative to the standard observations and analyses in the area. Broad cloud bands seen in the southwestern portions of the cyclone have been found to be nearly perpendicular to the wind direction at both the surface and aloft, and to consist mainly of cumuliform cloudiness whose tops did not extend more than about 5,000 ft. above the sea surface. Examination of the photographs relative to the conventional frontal analysis and to vertical motions computed by a numerical prediction model suggests that satellite cloud pictures can lead to improvements in the standard analyses of surface and upper-air charts.

1. INTRODUCTION

On two successive days early in April 1960 the experimental meteorological satellite, TIROS I, photographed portions of a cut-off cyclone in the eastern Pacific between Hawaii and California. One of the pictures (fig. 2) taken on the first of these days was so striking in its portrayal of broad, cyclonically curved, cloud bands, with superimposed smaller-scale cloud patterns, that it has already been illustrated several times in the early literature on the TIROS I pictures [1, 2, 3]. In the present paper this picture and several others taken on the same orbital pass and on another orbital pass over the storm about 23 hours later are examined in some detail. The cloud structure portrayed in these pictures is also interpreted in relation to the conventional synoptic observations and analyses, computed vertical motion fields, and the synoptic history of the storm.

2. DESCRIPTION OF PICTURES

Three photographs taken with the wide-angle camera on the first of the two days, April 4, 1960, at intervals of one minute starting at about 2250 GMT, are shown chronologically in figures 1–3. Each picture was obtained when the satellite was above the correspondingly numbered point in figure 8d, where isobars and fronts of the sea level analysis for 0000 GMT, April 5 by the National Weather Analysis Center (NAWAC) are shown. As is evident from the arrows in figure 8d between the sub-satellite points and the locations of the optical centers (principal points) of the pictures, figures 1–3 give views of the cloudiness in principally the western and southern quadrants of the storm.

The cloudiness illustrated in figure 2 (as well as in figs. 1 and 3) is remarkable for its broad, banded structure with narrow, relatively clear bands in between. The forward edges of these bands are generally quite sharp, whereas the rear edges tend to be diffuse. Note that the cloudiness behind lines AA and BB (figs. 1 and 2) appears to be predominantly of the cumuliform type, much of it with very interesting cellular structure (cf. Krueger and Fritz [4]).

A narrow-angle picture (fig. 4), encompassing the approximately square area outlined in figure 2, and taken 30 sec. after that picture, reveals very interesting details of the cloud structure straddling line BB. Note that the portion of line BB visible in figure 4 is quite clear-cut

*This research has been supported by the National Aeronautics and Space Administration.

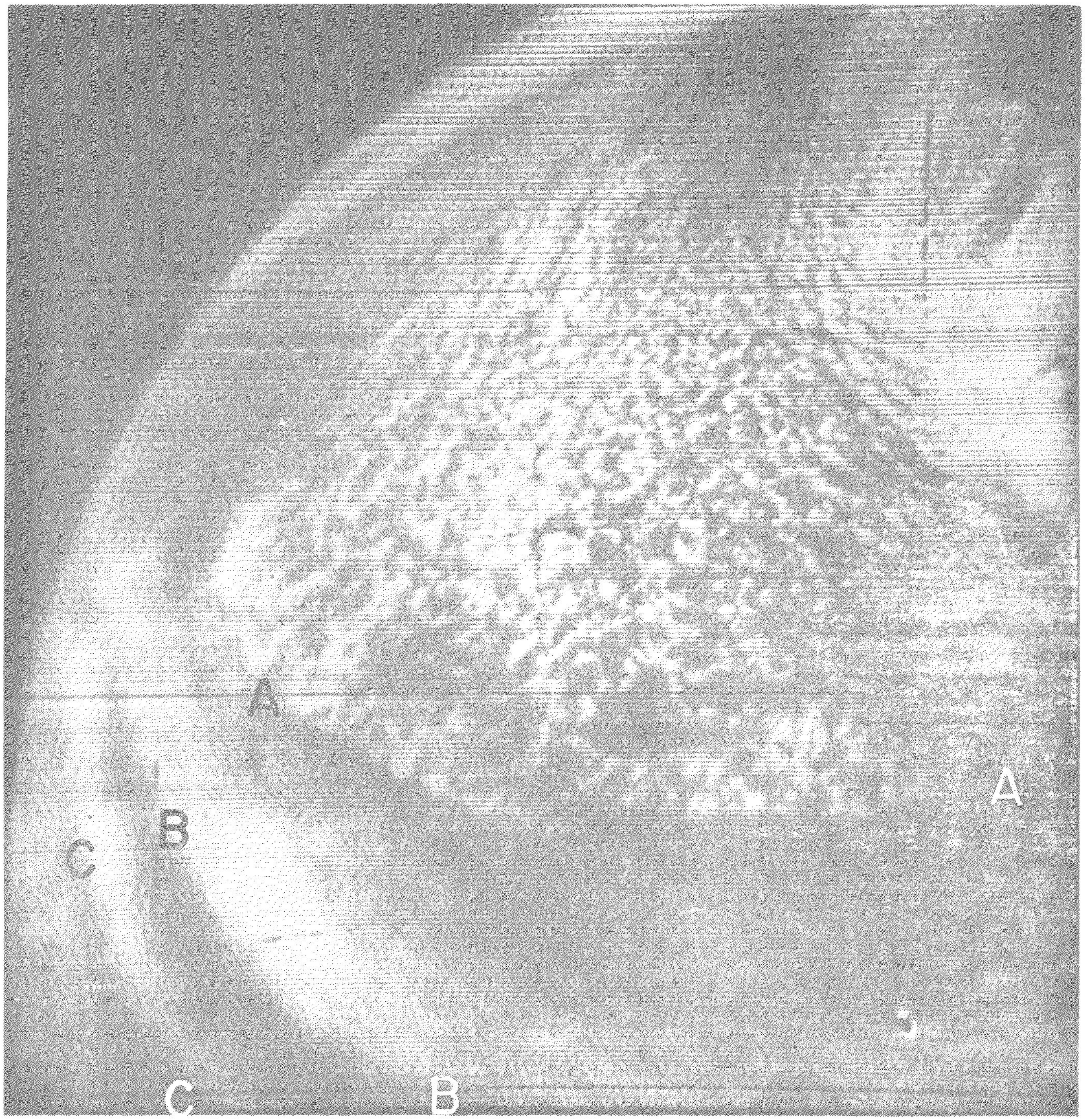

FIGURE 1.—Photograph of cloudiness west and southwest of cut-off cyclone in eastern Pacific showing principally cellular cumuliform cloudiness with sharp edge along line AA. Picture was taken at about 2251 GMT, April 4, 1960 when TIROS I was located above point 1 in figure 8d.

although it does not mark the edge of a solid wall of clouds. (Of course, this could also be determined to some degree from figure 2.) The cumuliform cloud elements which cover much of the area to the rear of this line appear to have a variety of sizes ranging from approximately 1 to 15 n. mi. in diameter. (The area visible in figure 4 is approximately 100 n. mi. on a side.) The cells in the upper right of this picture seem to merge together so that it is difficult to distinguish individual cells within these brighter cloud masses, which have a breadth of 20 n. mi. or more. When the wide-angle view (fig. 2) of this area seen in figure 4 is studied carefully (at least in a photo-print, if not in the printed reproduction available to the reader), some of these elements are barely discernible, but for the most part the clusters appear to be the basic cloud elements and one would on the average have to infer that they were composed of smaller-sized cumuliform cells. The area immediately ahead of line BB in figure 4 appears to be predominantly clear, but small, faint cumuliform cells with diameters of about 1 to 2 n. mi. cover much of the

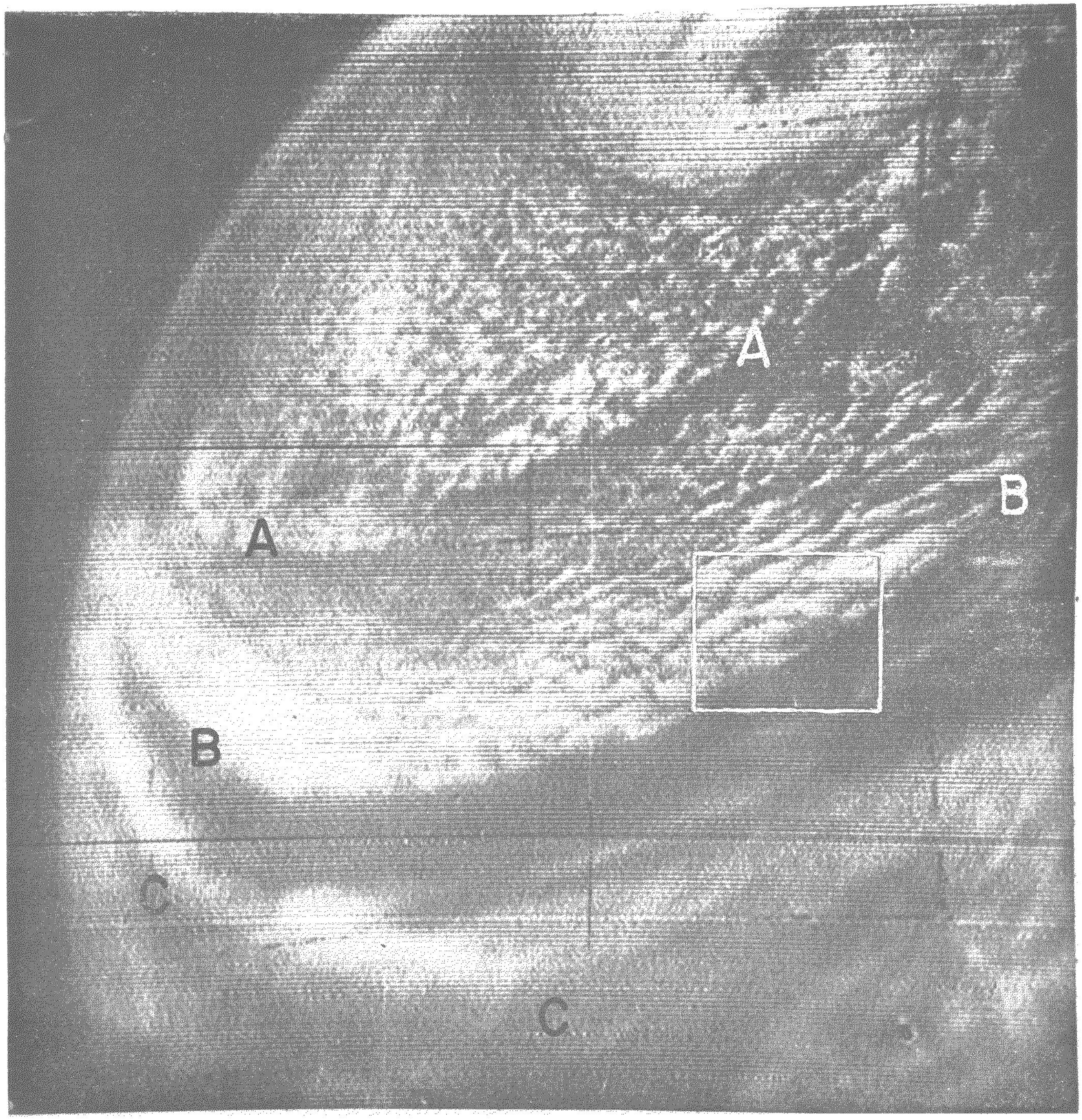

FIGURE 2.—Photograph of cloudiness southwest and south of cut-off cyclone in eastern Pacific showing pronounced lines, AA and BB, at forward edges of cumuliform cloud fields. Picture was taken at about 2252 GMT, April 4, 1960 when TIROS I was located above point 2 in figure 8d. The nearly square area outlined on the right side of the picture indicates the region viewed in a narrow-angle photograph shown in figure 4.

bottom and lower right portions of the picture. This structure is beyond recognition in figure 2, where only a wispy, gray shading is discernible.

The broad band of cloudiness behind line DD toward the upper right of figure 3 appears to have a more stratiform character than the cloudiness behind lines AA and BB. Very likely this represents the altostratus or cirrostratus tops of a cloud system rather extensive both horizontally and vertically. Toward the lower left the cloudiness in this band becomes more broken, and farther on a broad area of little cloudiness is found ahead of the relatively diffuse line designated as CC. The forward edge of the clouds along line DD is very sharp except where it is almost lost in some electronic "noise" toward the bottom of the picture. The line seems to have a more wavy character than lines AA and BB. This is portrayed in more detail in the narrow-angle picture (fig. 5) which gives a view 30 sec. later of the approxi-

FIGURE 3.—Photograph of cloudiness southeast through southwest of cut-off cyclone in eastern Pacific showing frontal cloudiness with sharp forward edge along line DD. Other pronounced lines along forward edges of clouds are the two seen more prominently in figures 1 and 2 (AA and BB) and the one along CC. Picture was taken at about 2253 GMT, April 4, 1960 when TIROS I was located above point 3 in figure 8d. The nearly square area outlined on the lower right side of the picture indicates the region viewed in a narrow-angle photograph shown in figure 5.

mately square area outlined in figure 3. This shows not only the larger-scale meanderings which can be perceived in figure 3, but also detailed scalloped cloud edges which convey the impression of a wall of cumuliform clouds typical of the leading edge of a pronounced cold front or squall line. Individual cellular elements are not distinguishable along this cloud line (as they are in fig. 4), which leads one to suspect that whatever cumulus clouds were present along this line were surmounted by a shield of middle or thick upper clouds. The other clouds visible in figure 5, to the right of the section of line DD just discussed, have outlines which are much more amorphous and are therefore suggestive of thick cirrostratus or altostratus cloud sheets.

Two wide-angle photographs of the storm on the second day, April 5, taken one and a half minutes apart ending at 2200 GMT, are shown in figures 6 and 7. The satellite path, sub-satellite points, principal points of the pictures,

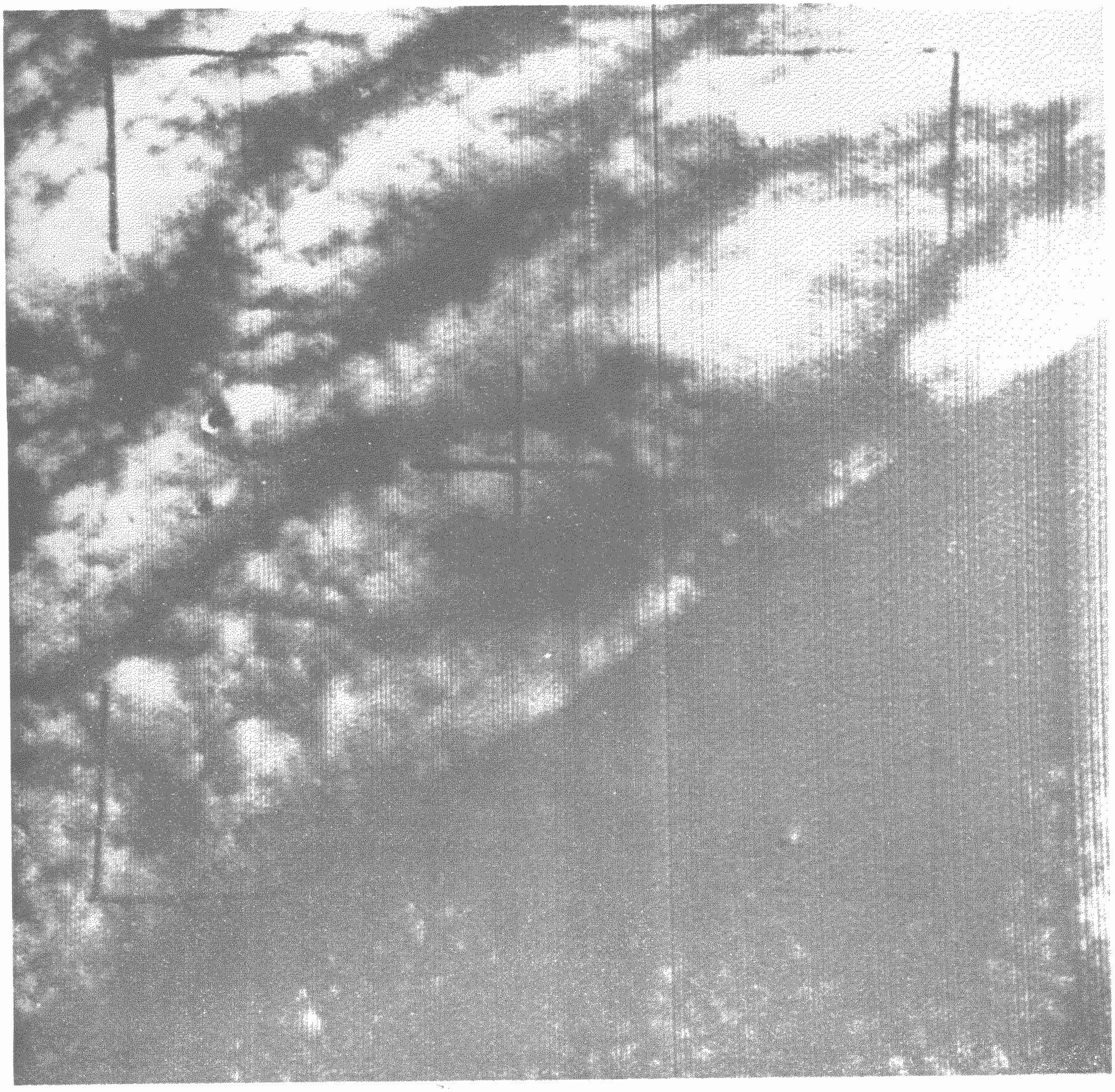

FIGURE 4.—Narrow-angle photograph showing details of cloudiness along a portion of line BB as indicated by the nearly square area outlined in figure 2. Picture was taken 30 sec. after wide-angle photo in figure 2. Several black dots (surrounded by bright white areas) in the middle left and lower right portions of the picture are due to flaws in the vidicon tube of the narrow-angle camera. Also, all pictures from this camera have a spurious darker swath running vertically through much of the middle of the picture.

and the NAWAC sea level chart for 0000 GMT, April 6 are illustrated in figure 8f. The pictures are oriented in approximately the same direction as before and therefore mainly cover the western and southern portions of the cyclone, but there is a better view in figure 7 of the central part of the storm than on the preceding day. The broad bands of cloudiness and alternating cloudlessness spiraling into the cyclone center are especially outstanding and resemble strongly the classical cyclonic spial as observed in the laboratory (cf. [5], [6]) and in tropical storms with radar [7]. Although a fair degree of cellular structure is still evident in these two pictures, the areas of cellular cloudiness on the west and south sides of the cyclone center have generally diminished, as compared with the preceding day.

3. SYNOPTIC HISTORY OF THE STORM

The evolution of this major cyclone is illustrated by a series of NAWAC sea level analyses at 12-hr. intervais (fig. 8). On April 3 at 1200 GMT (fig. 8a) a broad cyclonic

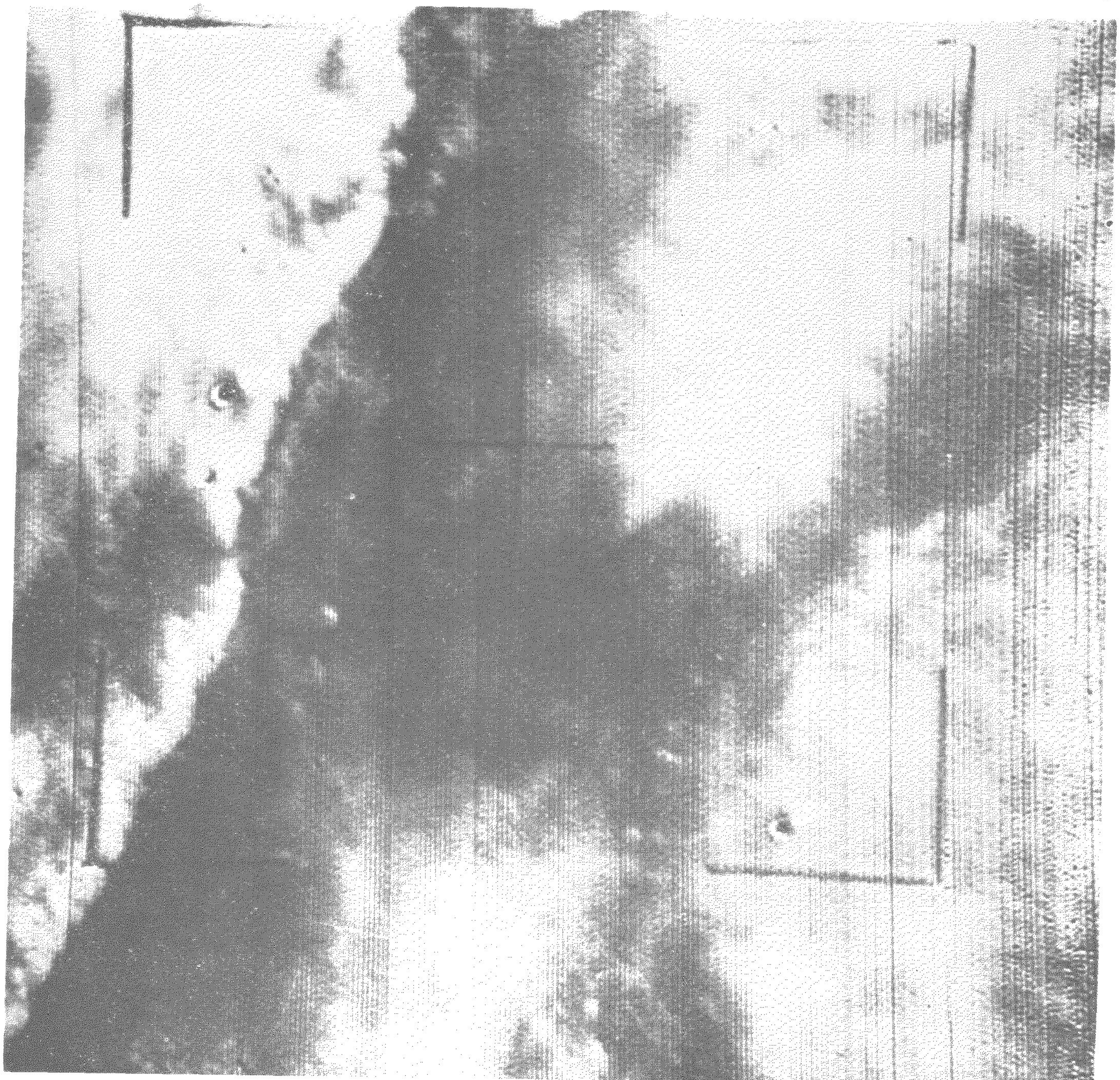

FIGURE 5.—Narrow-angle photograph showing details of cloudiness along a portion of line DD as indicated by the nearly square area outlined in figure 3. Picture was taken 30 sec. after the wide-angle photo in figure 3. (See legend to figure 4 regarding defects in narrow-angle camera.)

circulation existed over the eastern Pacific from the Gulf of Alaska southward toward about latitudes 30°–35°N. The major center of low pressure in this cyclonic complex had just moved northeastward to a position near 48°N., 140°W. in the previous 24 hours. The system with which we are concerned had its origin in the small perturbation located near 39°N., 155°W. In typical fashion this center and the cold front extending to its west were moving generally southeastward along the periphery of the main cyclone center. At 0000 GMT, April 4 (fig. 8b) a new center apparently started forming farther southward along the frontal trough at about 34°N., 150°W. By 1200 GMT, April 4 (fig. 8c) the system was organizing into a closed cyclonic circulation with pressures increasing to the north. Also, a weaker pressure minimum was located to the east along the main polar front near 33°N., 139°W. By 0000 GMT, April 5 (fig. 8d), one hour after the pictures in figures 1–5 were taken, an extensive cyclonic circulation had become established owing to both the deepening of the new cyclone center and the increases in pressures to the north of the

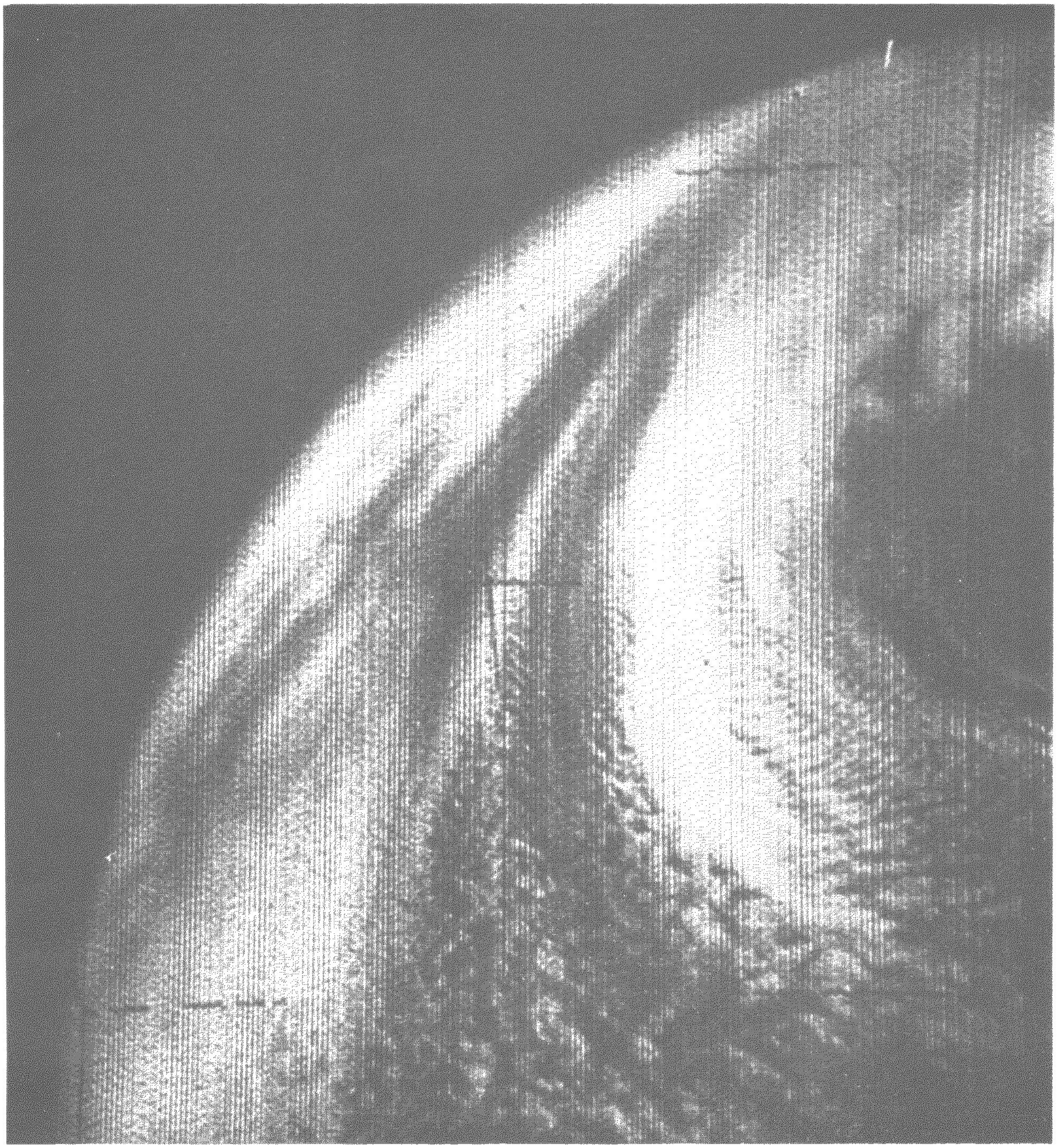

FIGURE 6.—Photograph of cloudiness west and southwest of cut-off cyclone in eastern Pacific on day following views in figures 1–5, showing broad, cyclonically curved band west of clear area closer to storm center. Picture was taken at about 2159 GMT, April 5, 1960 when TIROS I was located above point 6 in figure 8f.

Low. Note that the NAWAC frontal analysis on this map had been simplified in that the secondary cold front was dropped and therefore a front no longer extended into the storm center. Twelve hours later at 1200 GMT, April 5 (fig. 8e) the cyclone reached its lowest central pressure (about 999 mb.) and had about the strongest isobaric gradients and hence probably the strongest surface wind field (as viewed on 6-hourly charts). By 0000 GMT, April 6 (2 hours after the pictures shown in figs. 6 and 7 were taken) the storm had begun to fill and surface winds were weakening considerably (fig. 8f). Thus the two sets of TIROS pictures show portions of the storm about 12 hours prior to and about 12 hours after its most intense stage.

The history of the storm at upper levels is not especially notable except that a closed upper center was analyzed at 700 and 500 mb. as the center deepened. However, the paucity of radiosonde observations in the region left the precise intensity of the upper center somewhat in doubt.

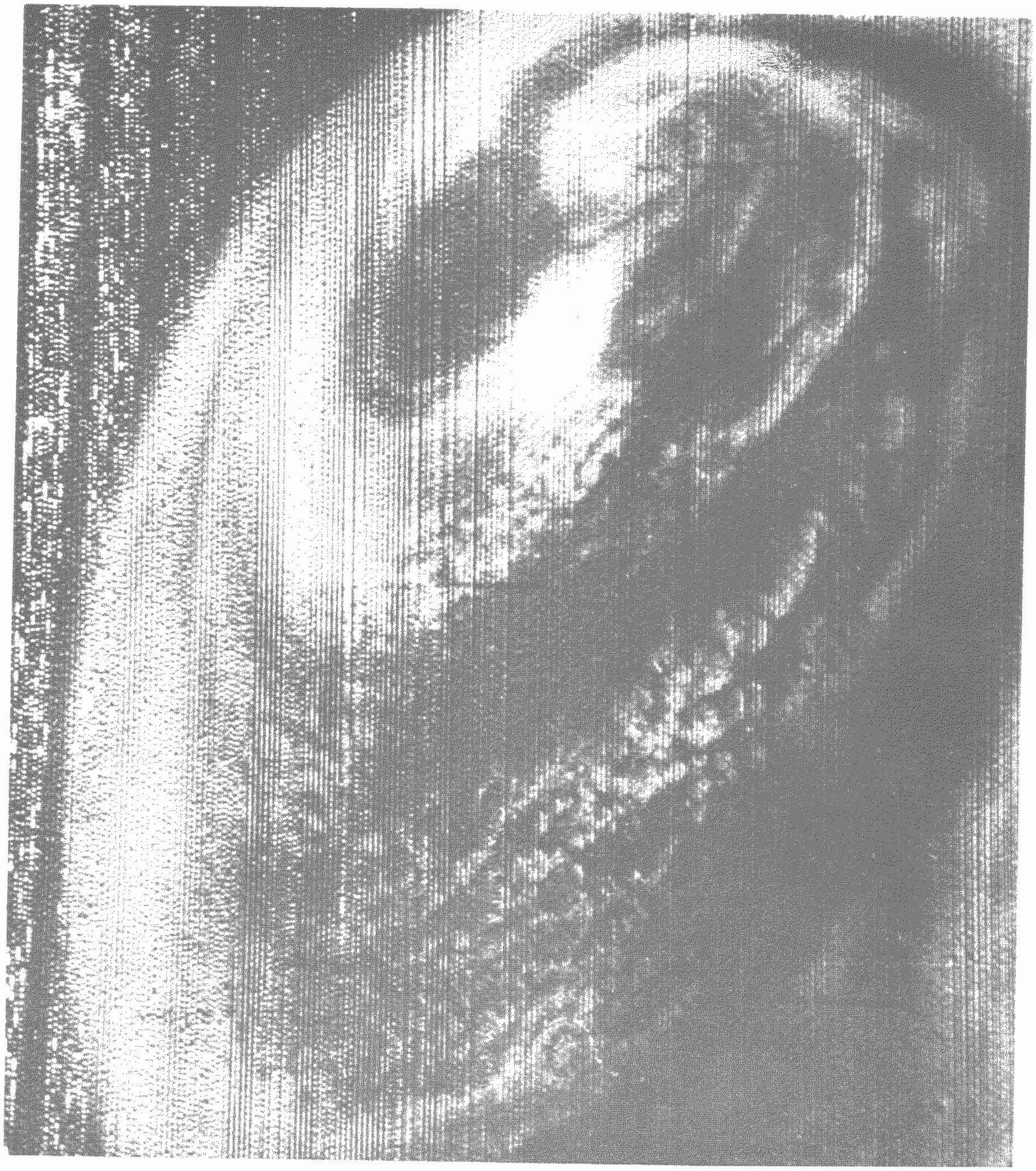

FIGURE 7.—Photograph of cloudiness around center and southeast through southwest of cut-off cyclone in eastern Pacific on day following views in figures 1–5, showing pronounced spiral bands near center and several zones of cumuliform cloudiness well to the south of the center. Picture was taken at about 2200 GMT, April 5, 1960, one and a half minutes after figure 6, when TIROS I was located above point 7 in figure 8f.

4. RELATION OF THE CLOUD PICTURES TO CONVENTIONAL METEOROLOGICAL INFORMATION

Although the TIROS pictures can be compared visually with the standard synoptic weather data and charts once the satellite's location and general orientation are known, it is not until complete latitude-longitude grids are superimposed on the pictures that detailed and moderately accurate comparisons are feasible. Such gridding has been achieved for the pictures in this case by methods described in [8].

The pictures taken at about 2250 GMT, April 4, which have already been presented in figures 1–3, are shown in figures 9–11 with a 2° latitude-longitude grid, surface isobars and fronts from the NAWAC analysis, abbreviated surface synoptic reports, and pilot reports of clouds, all superimposed. The pictures are shown again in figures 12–14 with superimposed grid, 700-mb. contours, radiosonde reports, pilot reports of winds in the mid-troposphere, and vertical motion at 600 mb. as computed by the Joint Numerical Weather Prediction (JNWP) Unit.

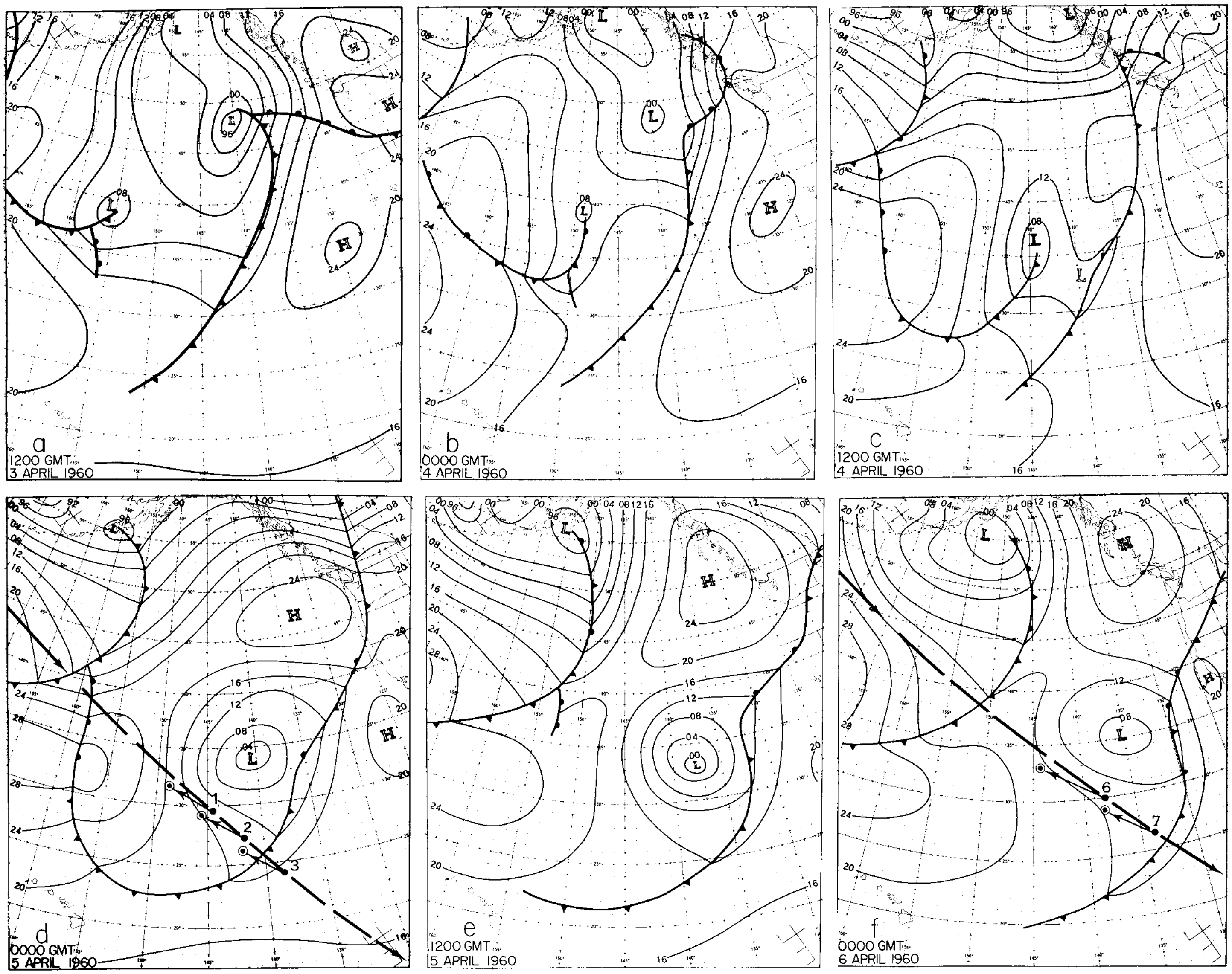

FIGURE 8.—Sequence of NAWAC sea level analyses at 12-hour intervals showing the evolution of cut-off cyclone in eastern Pacific. Paths of TIROS I on two days when pictures were taken of this area are shown in d and f. For wide-angle pictures discussed in this report, sub-satellite points are indicated by dots, principal points of pictures by circled dots, and horizontal orientation of camera by arrows in d and f. Numbers identify locations for pictures shown in figures 1–3, 6, 7.

All data except the pilot reports are for 0000 GMT, April 5.

The most striking feature of figures 9–14 is that most of the major bands are nearly perpendicular to the surface isobars and 700-mb. contours. Only line DD, which is related to the main cold front, and the northeastern end of line BB are closely parallel to the mid-tropospheric flow. It is well known however that there are frequently convergence lines in the westerly and northwesterly flow of cold air to the rear of well-defined cyclones. Such lines appeared frequently in the detailed analyses by members of the Bergen school (cf. [9]), some of them actually identified as "bent-back" occlusions or secondary cold fronts. In recent years, particularly on maps of a hemispheric scale, there has been more of a tendency to exclude these more minor systems from the analyses.

In the case under discussion here it appears that lines AA and BB are very likely convergence lines of this type. Close investigation of the position of line BB as compared with the secondary cold front analyzed on preceding NAWAC sea level charts (fig. 8) indicates rather strongly that line BB is indeed associated with this very same surface front. Its rather close fit with previous 6-hourly positions of the front as carried on the NAWAC analyses is illustrated in figure 15. In addition it is interesting that the surface analysis made by the Weather Bureau Forecast Center at San Francisco (not shown), which was consulted after the initial preparation of figure 15, retained the second front and its position coincides closely with that shown for line BB in figure 15.

Inspection of the superimposed 600-mb. vertical motion

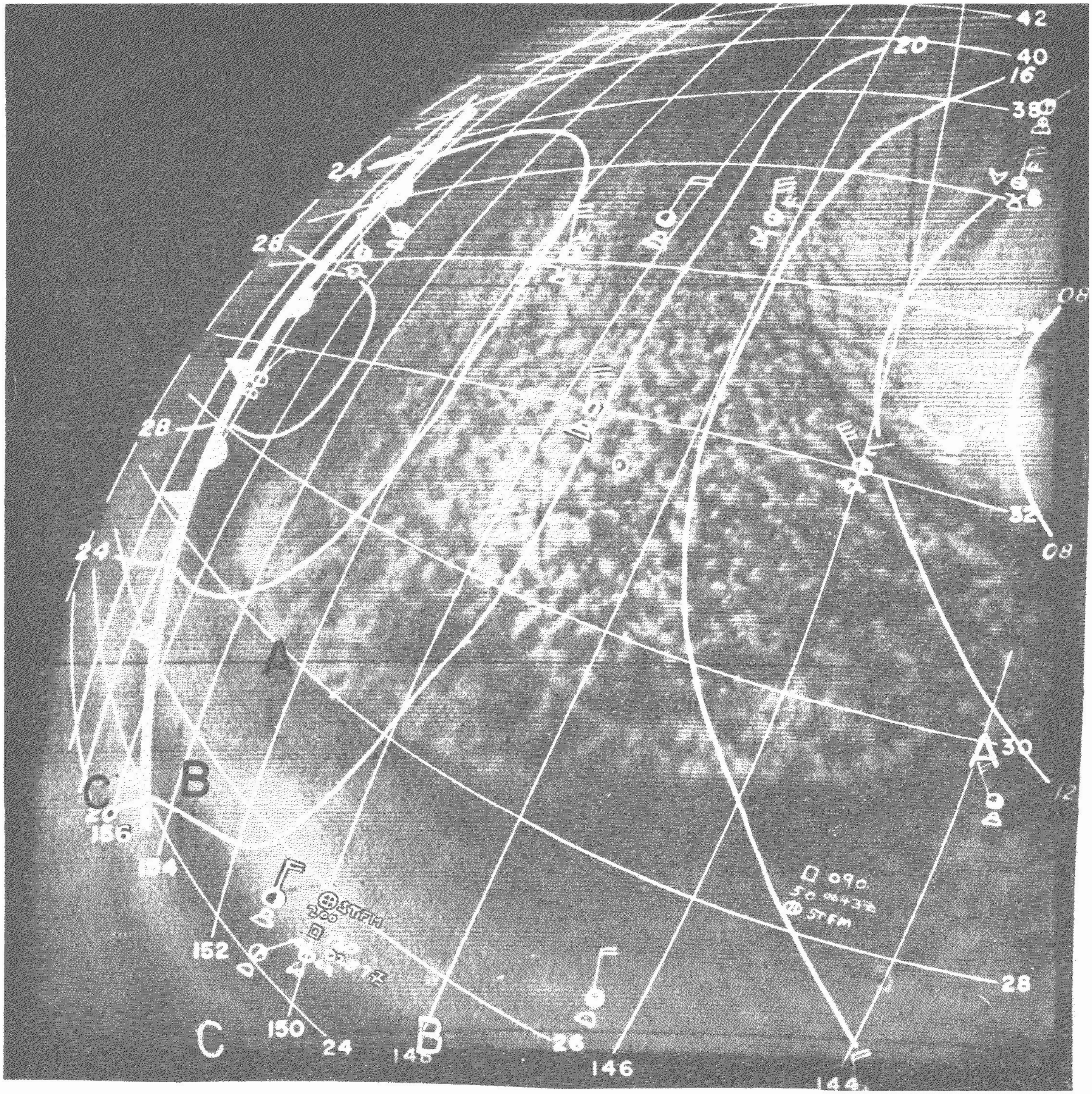

FIGURE 9.—Same picture as in figure 1 with superimposed 2° latitude-longitude grid; principal point of picture (circled dot); sea level fronts and isobars at 4-mb. intervals; abbreviated surface reports showing sky cover, cloud types, present weather, and winds; and pilot reports (squares), for times indicated, of types, amounts, and heights (in hundreds of ft.) of bases and/or tops of clouds. Time of superimposed data, except pilot reports, is 0000 GMT, April 5, 1960.

field, which consists of initial vertical velocities computed from a two-level baroclinic model by the JNWP Unit, shows a pattern of large-scale vertical motion which has been found to be typical of trough systems as exemplified by the 700-mb. contours in figures 12–14 (i.e., downward motion to the rear of the trough and upward motion ahead of the trough). It is notable that the area to the rear of line DD (fig. 14), which appears to be a zone of cloudiness extending upward into the middle and upper troposphere, is associated with the main polar front (fig. 11) where slight upward motion was calculated. However, the southwest-northeast orientation of this cloud band, with mostly clear

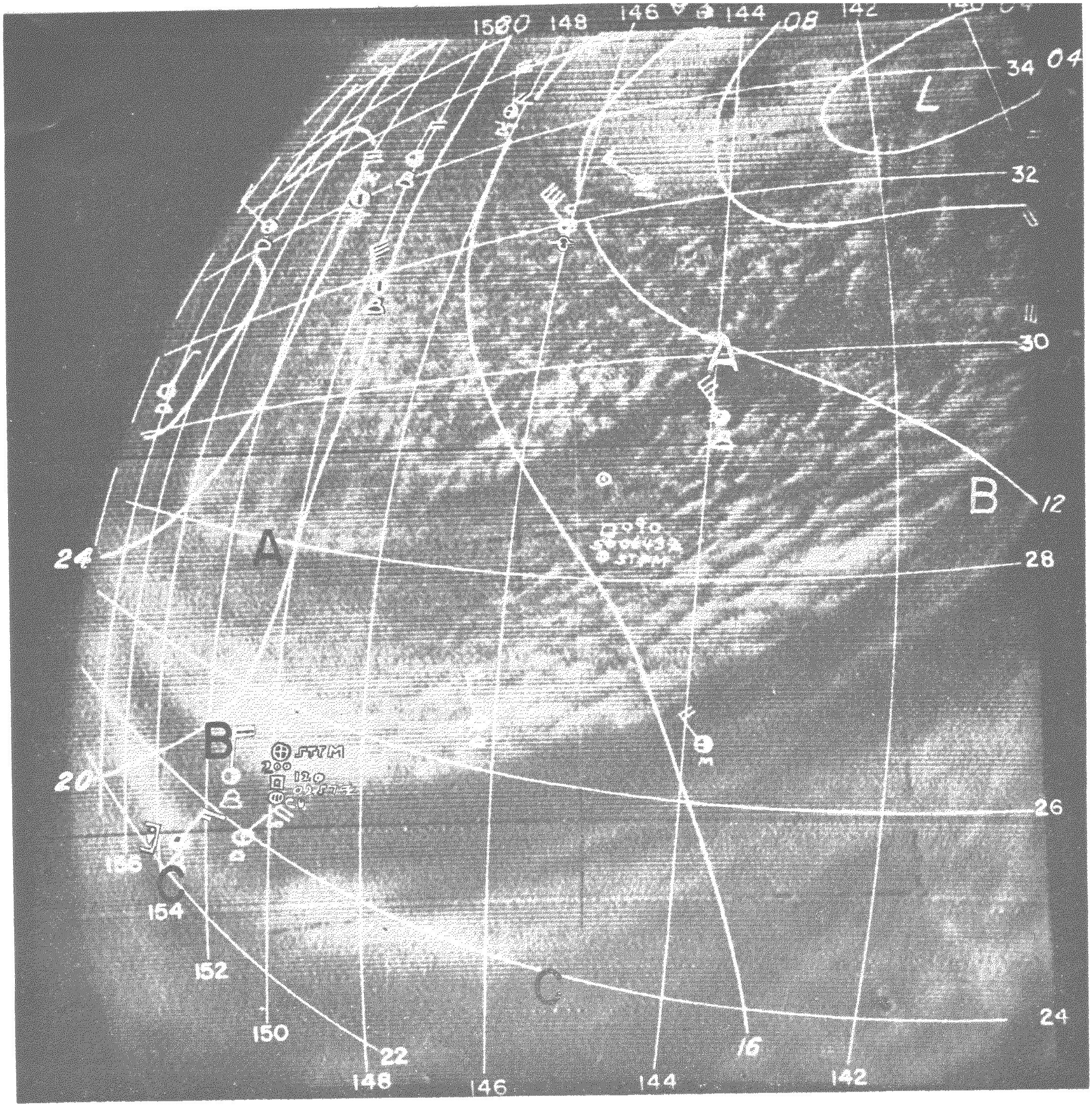

FIGURE 10.—Same picture as in figure 2 with superimposed grid and other items as in figure 9.

skies to the east of DD, suggests that the axis of maximum upward motion might be elongated southwestward to coincide more closely with this band.

Most of the remaining areas of the pictures, including lines AA, BB, CC, and the cloud areas behind them, are located where downward motion was computed. At first glance it seems surprising that such pronounced zones of cloudiness as those occurring along and to the rear of lines AA and BB should be found where the large-scale vertical motion was downward. However, this may indeed be physically correct since most evidence points to the fact that the cloudiness in these areas was of the cumuliform type which was very likely confined to approximately the lower 5000 ft. Certainly most of the clouds reported by ships in these areas were cumulus congestus and stratocumulus. A pilot report at 29.5° N., 145° W., about 8

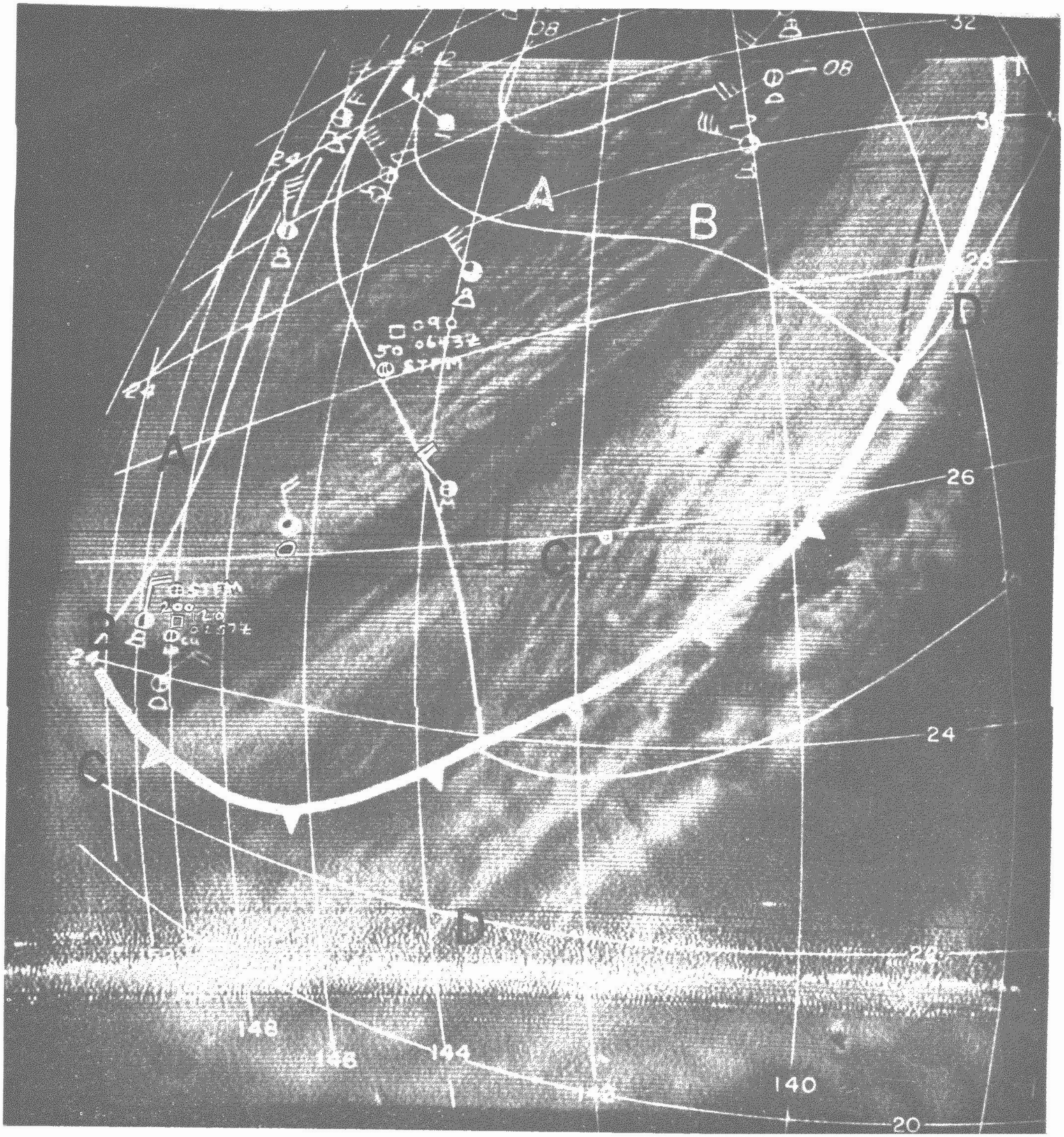

FIGURE 11.—Same picture as in figure 3 with superimposed grid and other items as in figure 9.

hours after the pictures were taken, indicated broken stratiform (presumably stratocumulus) clouds with tops at 5000 ft. The soundings at 35° N., 150° W. (fig. 16), which was well back in the cellular cloudiness to the rear of line AA, and the sounding at 30° N., 140° W. (fig. 17), which was practically on line BB, both reveal a moist, unstable layer of air from the surface to about 850 mb., with a layer of stable, dry air extending from above the pronounced inversion upward to near 600 mb. These soundings certainly suggest that cloudiness in their vicinities would have been confined to the instability type in the layer below the inversion. If convergence was indeed associated with lines AA and BB, it must therefore have been horizontal convergence and upward motion confined to this lower layer.

In portions of these areas, however, there is some evi-

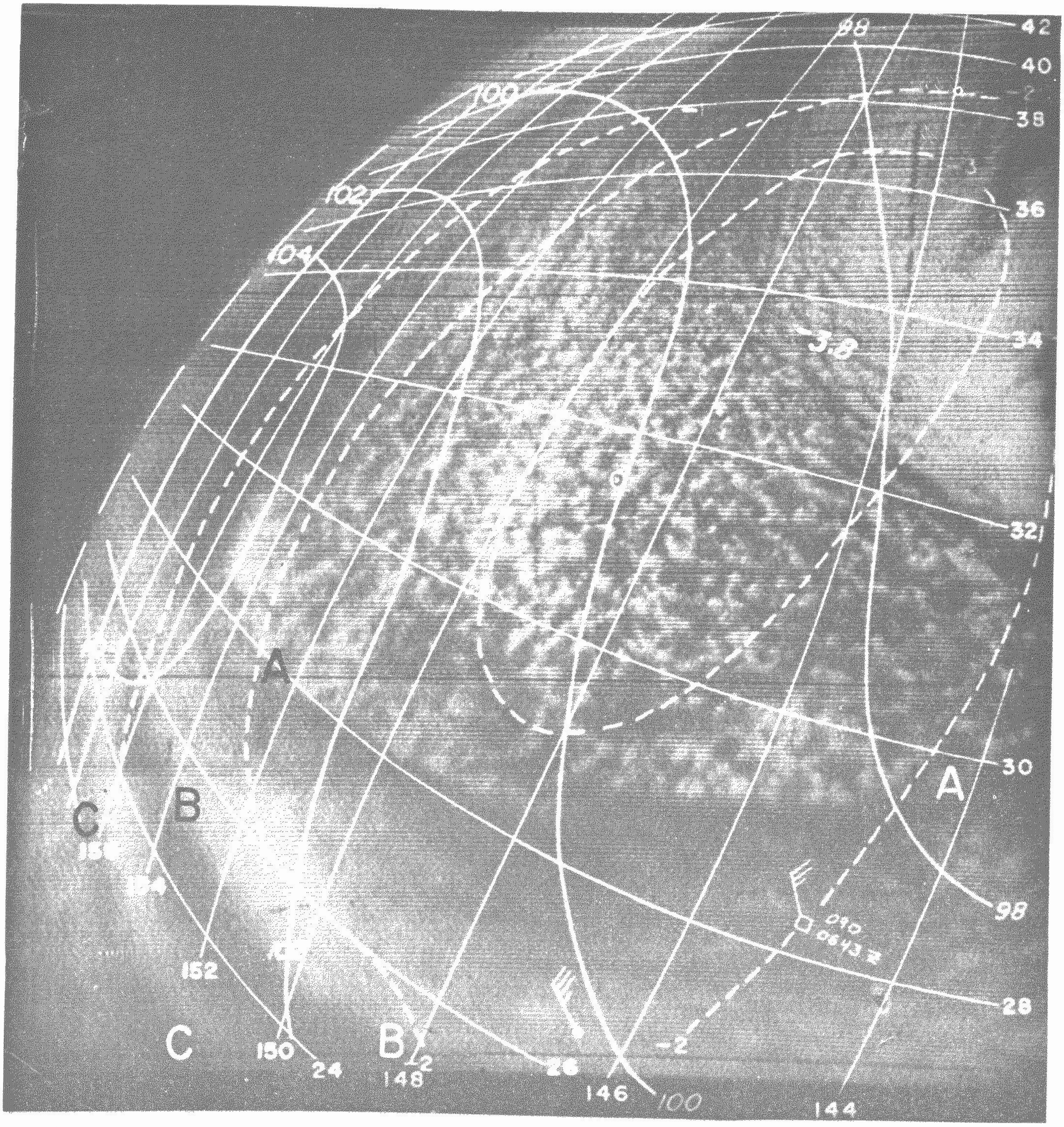

Figure 12.—Same picture as in figure 1 with superimposed 2° latitude-longitude grid; principal point of picture (circled dot); 700-mb. contours at 200-ft. intervals; 700-mb. winds; winds between 8000 and 12,000 ft. from aircraft measurements; and 600-mb. vertical motion in cm. sec.$^{-1}$ as computed routinely by the JNWP Unit. Time of superimposed data, except pilot reports, is 0000 GMT, April 5, 1960.

dence of middle cloudiness. Note the ship report of altostratus near 35° N., 148° W. which is just near the western edge of a solid-looking (apparently stratiform) cloud shield (fig. 9). Also the pilot report at 25° N., 150° W., approximately 4 hours after the picture was taken, shows an overcast of a stratiform type (presumably altostratus or cirrostratus) at an estimated base of 20,000 ft. (fig. 9). This report is also in a region where the cloudiness has a stratiform appearance. As the complete pilot report suggests, this upper cloud deck at this point overlay the lower, more extensive cumuliform cloudiness characteristic of the area behind line BB. The presence of middle cloudiness in

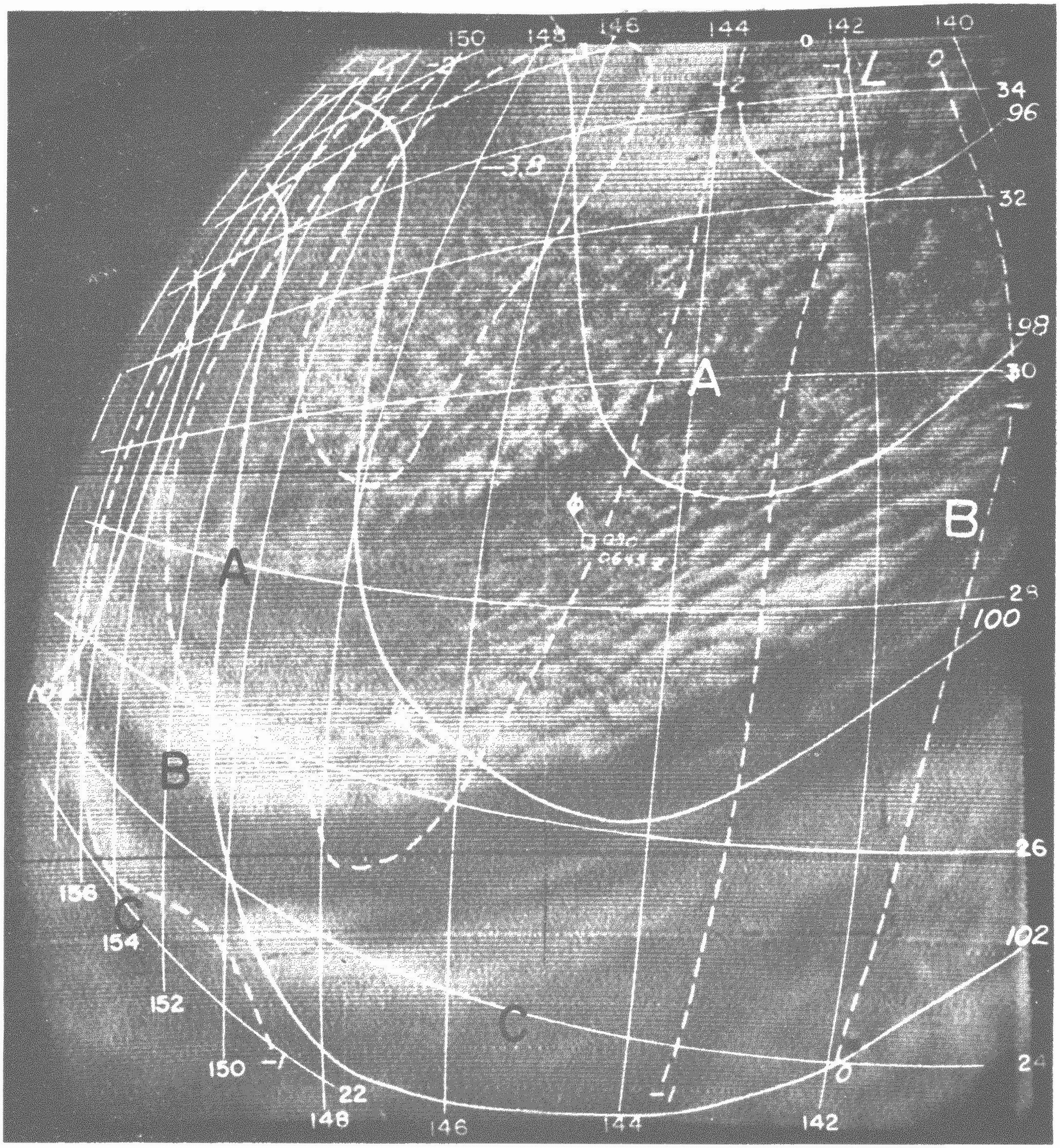

FIGURE 13.—Same picture as in figure 2 with superimposed grid and other items as in figure 12.

these areas suggests the likelihood of some large-scale upward motion in mid-troposphere.

Gridded pictures taken near 2200 GMT, April 5 (previously illustrated in figs. 6 and 7), are shown in figures 18–21 with superimposed NAWAC surface and 700-mb. analyses, abbreviated synoptic surface reports, and 600-mb. vertical motion, all of which are for 0000 GMT, April 6. It is notable that the broad banded cloud structure to the west of the cyclone (fig. 18) is closely oriented in th direction of the surface isobars. The ship reports shov stratocumulus, cumulus congestus, and low clouds of ba weather in the area under this broad, bright band; ther are also a few reports of an altostratus-altocumulus laye above the lower clouds. In view of the presence of middl cloudiness in this band, it is somewhat surprising that th 700-mb. contours are so different in orientation from th

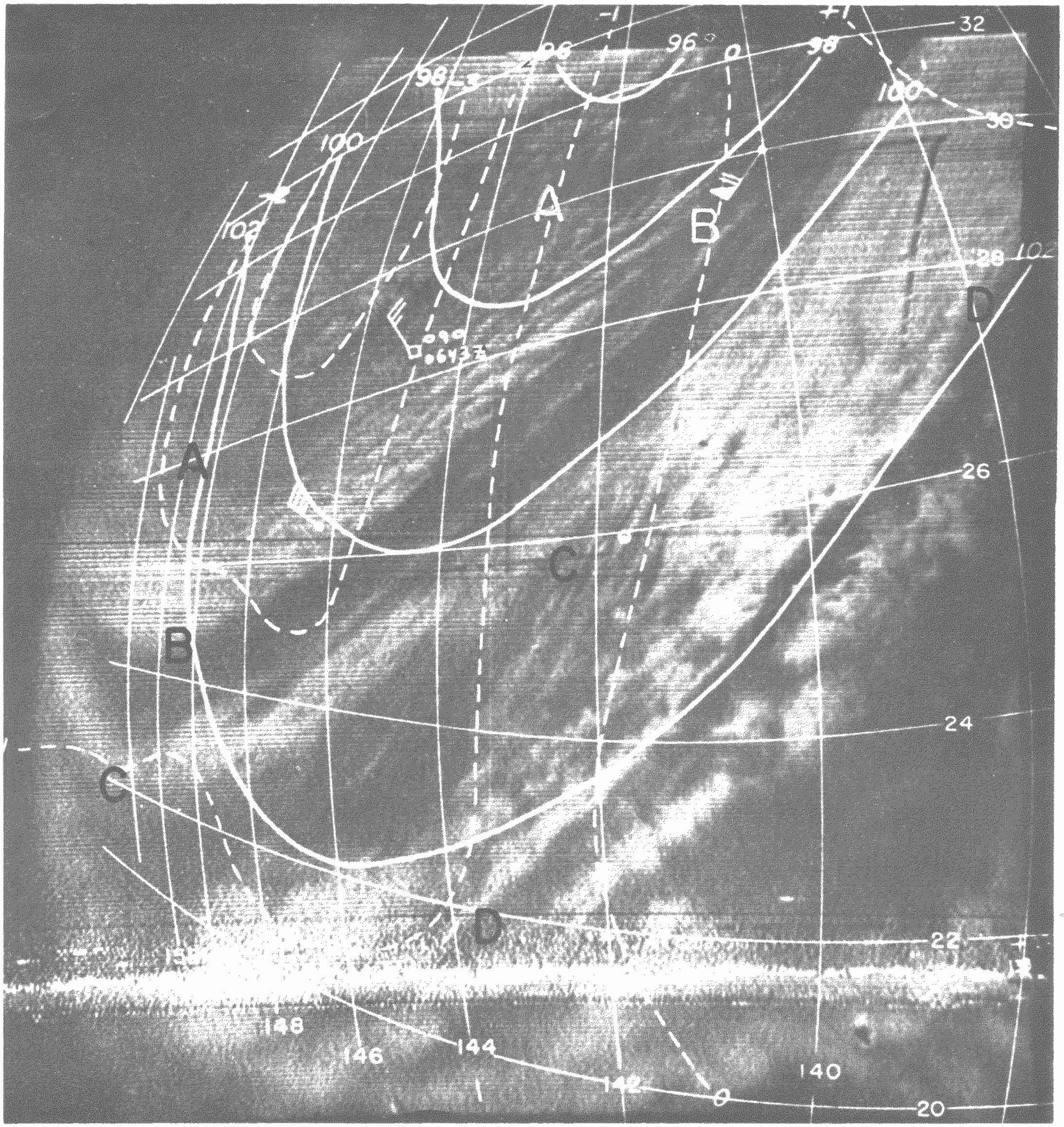

FIGURE 14.—Same picture as in figure 3 with superimposed grid and other items as in figure 12.

sea level isobars and the cloud band (e.g., the band and the contours are nearly perpendicular to each other near 34° N., 142° W. in fig. 20). The question thus arises as to whether the anticyclonic curvature in the 700-mb. contours is consistent with the pronounced cyclonic curvature of the sea level isobars. Twelve hours earlier the two analyses showed a close correspondence in flow patterns at the two levels (both strongly cyclonic). Although some height rises undoubtedly occurred in this 12-hour period, it does appear that this 700-mb. analysis eliminated the cyclonic curvature in the region of this cloud band too rapidly. It is likely that the 700-mb. contours actually did have an orientation more nearly parallel to the cloud band and to the surface isobars. In

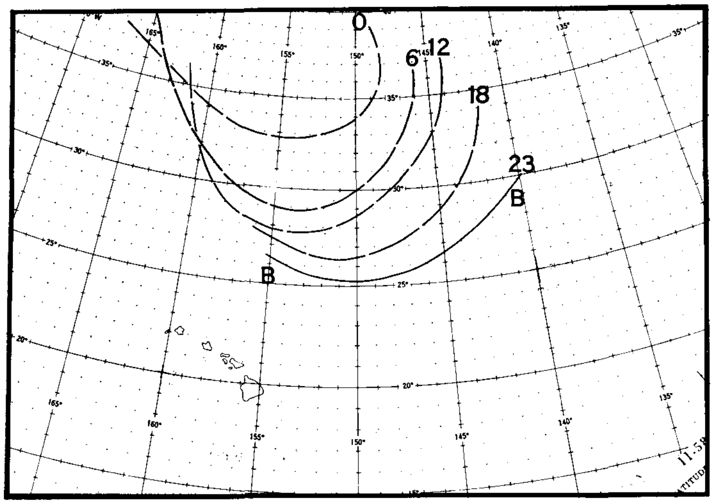

FIGURE 15.—Continuity of secondary cold front on April 4, 1960. Labeled positions for 0000, 0600, 1200, and 1800 GMT are from NAWAC sea level analyses. The position of line BB at 2300 GMT was derived from the gridded photograph in figure 10.

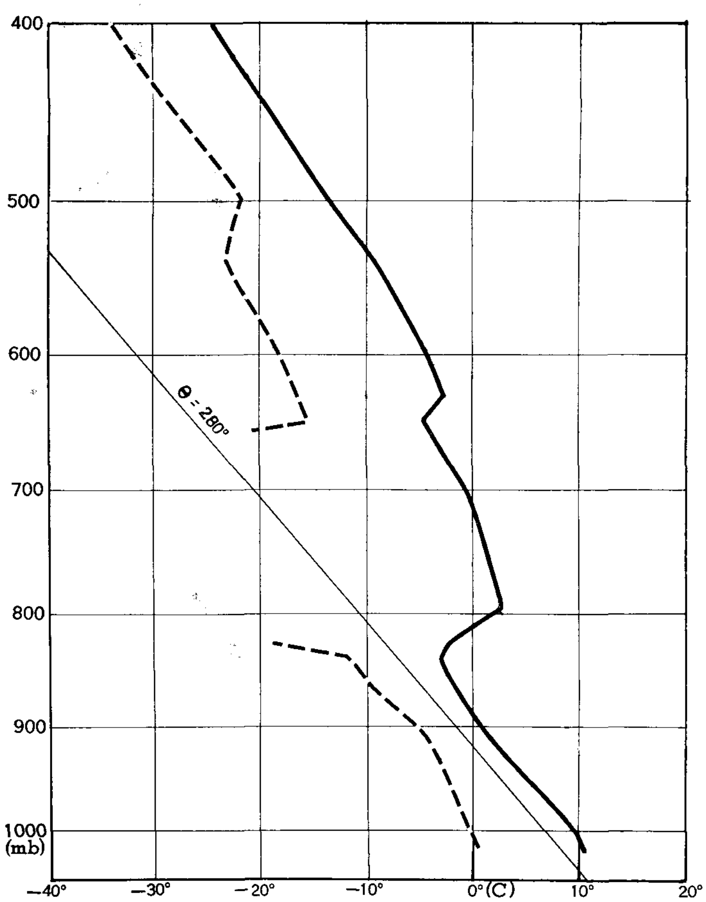

FIGURE 16.—Sounding at ship NHXN (34.9° N., 150.4° W.), 0000 GMT, April 5, 1960. Solid line shows temperature distribution; dashed line, dew point distribution.

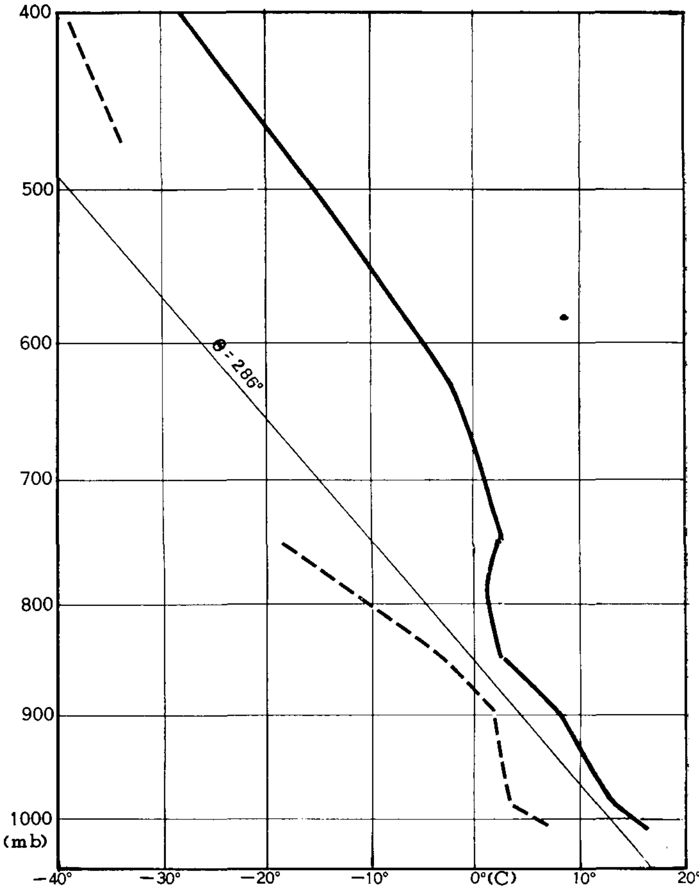

FIGURE 17.—Sounding at ship 4YN (30.0° N., 140.0° W.), 0000 GMT, April 5, 1960. Solid line shows temperature distribution: dashed line, dew point distribution.

fact it can be demonstrated readily that the contours can be reanalyzed in this fashion without violating any data.

The bands spiraling into the center of the storm as shown in figure 19 appear to line up with the surface flow north and just east of the center of the Low, although there is some uncertainty of this in view of the center's location toward the edge of the picture, where the accuracy of locating picture elements diminishes. The bands to the south of the cyclone center form a moderate angle of about 30°–45° with the surface isobars near 30° N., 134° W. and this increases to about 90° farther southwestward near 28° N., 138° W. It is probable that the forward edge of the spiral band which emanates from the center and runs approximately through 36° N., 134° W., southeastward to 32° N., 131° W., and thence southwestward through 28° N., 134° W. is the remnant of line BB in the pictures for the previous day (e.g., see fig. 10). This is supported by some rough trajectory calculations, based on the previous day's position of line BB, which show that this continuity from 24 hours earlier is within reason. The primary cold front appears to be mainly off the edge of the picture, but the cloud band near the northeastern and southeastern edges of the picture is very likely part of this frontal system and the suggestion is

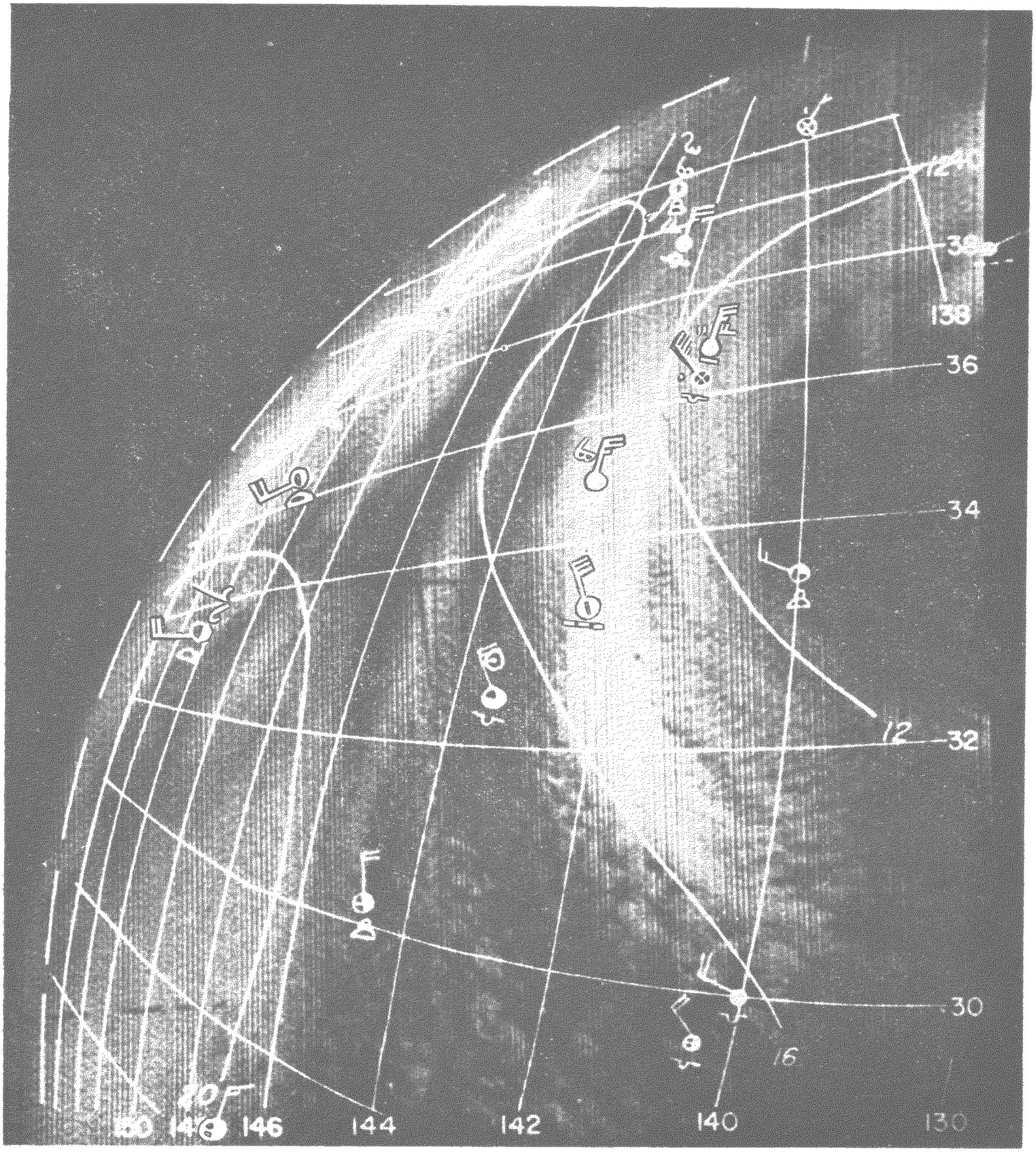

FIGURE 18.—Same picture as in figure 6 with superimposed grid and other items (except pilot reports) as in figure 9, except that time of superimposed data is 0000 GMT, April 6, 1960.

that the cloudiness and perhaps the front itself have spiraled into the region just north of the surface low center.

The vertical motion fields shown in figures 20 and 21 again fit in with the general broad-scale distribution expected around the mid-tropospheric trough associated with the cyclone. However, the solid-looking spiral bands and alternating clear areas near the cyclone center suggest that there may have been a similar spiraling of the vertical motion pattern in both the lower and middle troposphere. The JNWP vertical motion field is perforce constrained to a simpler pattern because of the general smoothing applied in the numerical calculations and because of the paucity of upper-air observations over this ocean area. It would be interesting to learn whether knowledge of such a spiral arrangement of vertical motion could sub-

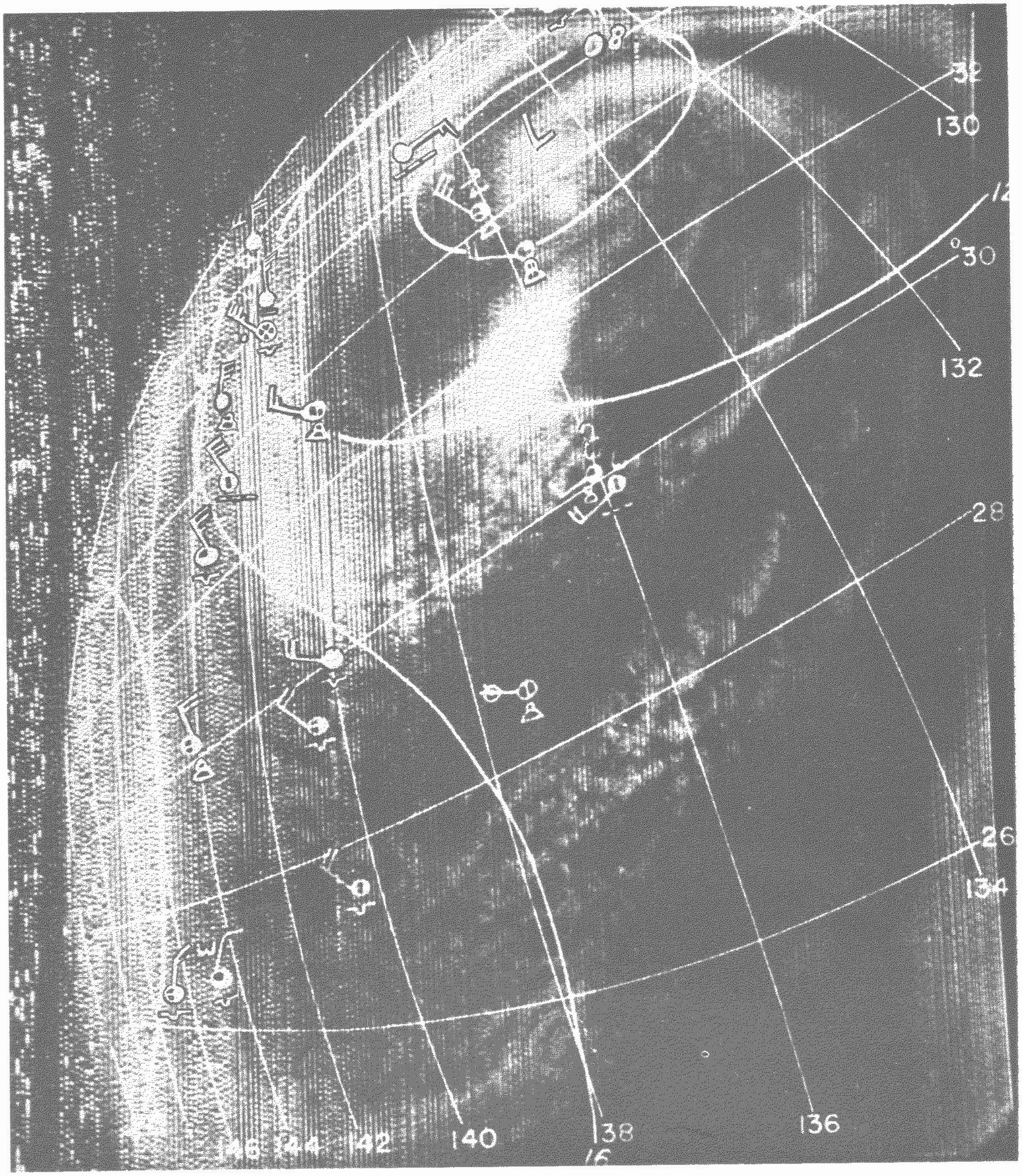

FIGURE 19.—Same picture as in figure 7 with superimposed grid and other items (except pilot reports) as in figure 9, except that time of superimposed data is 0000 GMT, April 6, 1960.

stantially improve predictions of the further evolution of the cyclone.

5. SUMMARY

The TIROS cloud pictures portray the details of the cloud structure around portions of this cut-off cyclone in the eastern Pacific in strikingly clear fashion. It has been shown that some of the major cloud bands in the southwestern portion of this cyclone were nearly perpendicular to the wind direction at both the surface and aloft. Also one of the most pronounced of these bands was identified as a secondary cold front along which the cyclonic development took place. The cloud patterns viewed by TIROS suggest possible modifications in the patterns of computed large-scale vertical motion in the middle troposphere. Regular views of entire storm areas, even at intervals of a day, would enhance our understanding of the life cycle and structure of systems such as the cut-off cyclone studied in this report.

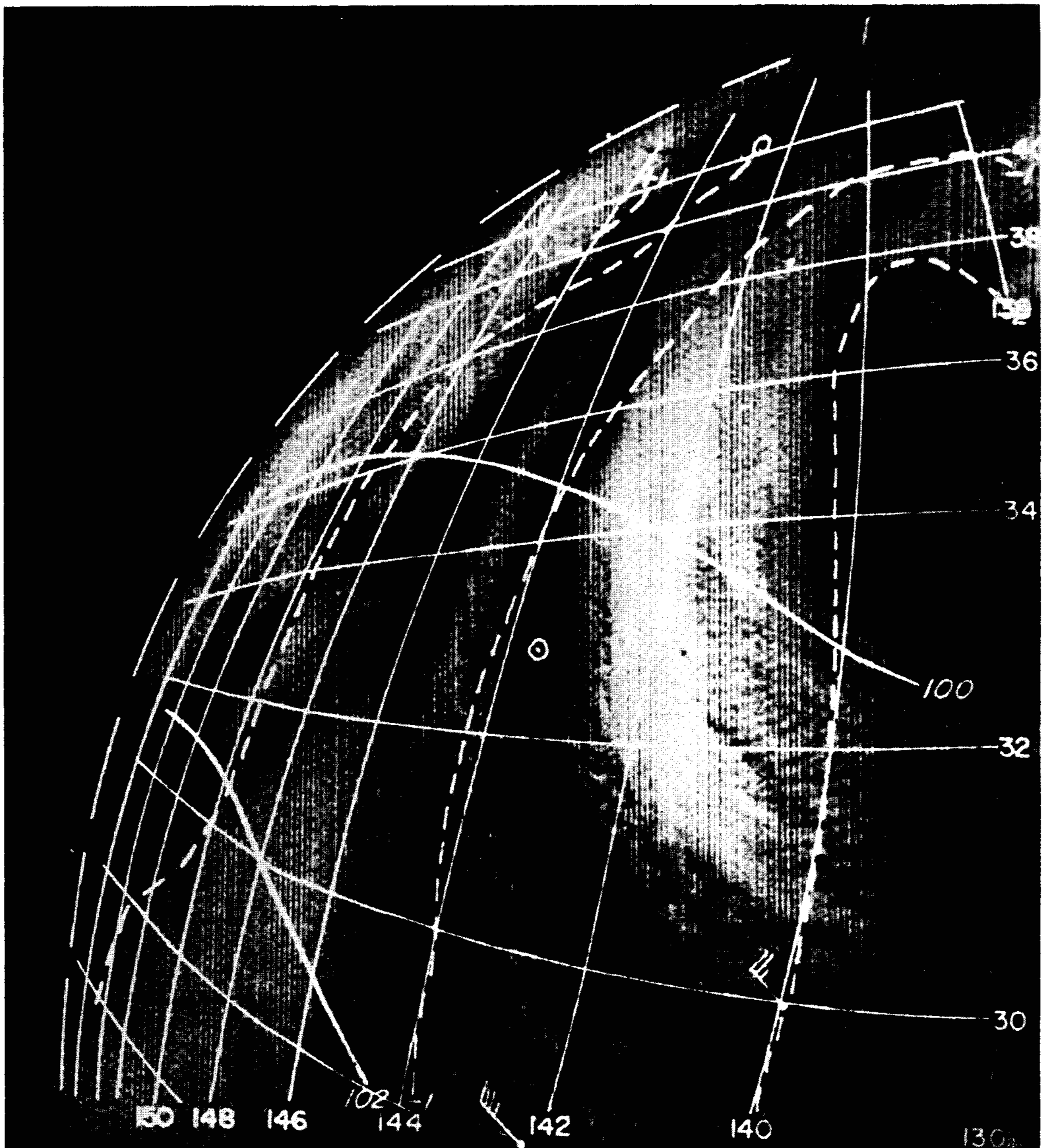

FIGURE 20.—Same picture as in figure 6 with superimposed grid and other items as in figure 12, except that time of superimposed data is 0000 GMT, April 6, 1960.

ACKNOWLEDGMENTS

The assistance of Louis Rubin in preparing the pictures with superimposed grids, isopleths, and plotted observations and of George E. Martin in fitting latitude-longitude grids to the pictures is sincerely appreciated.

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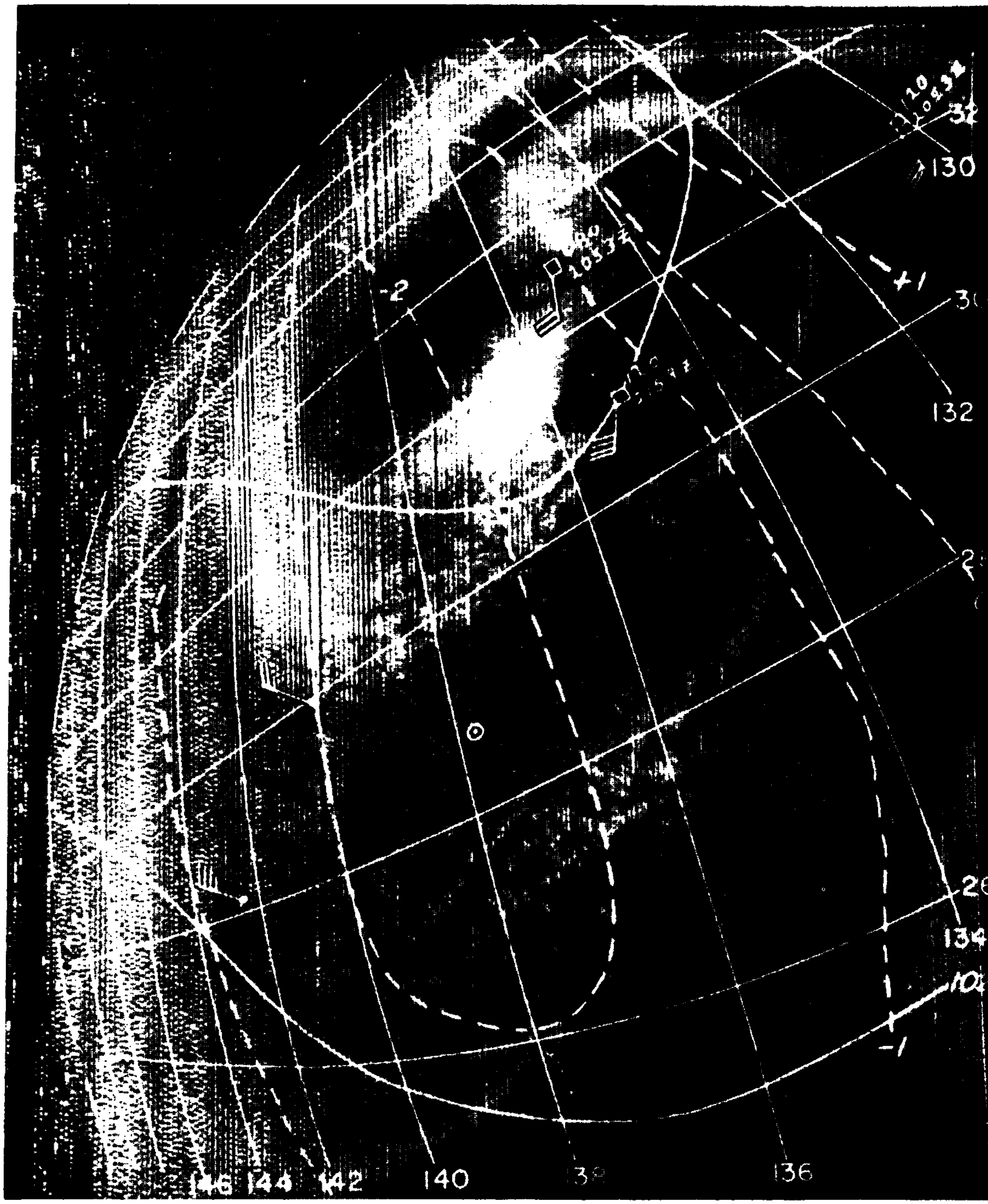

FIGURE 21.—Same picture as in figure 7 with superimposed grid and other items as in figure 12 except that time of superimposed data is 0000 GMT, April 6, 1960.

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